Explosive welding

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by B. Crossland and J. D. Williams

Explosive welding, which is a solid-phase welding process, was probably discovered by chance by Philipchuk,[1]* who states that he first observed the effect when explosively forming an aluminium U-channel on a steel die. It was found that the U-channel could not be removed from the die because a circular-shaped area had become welded to the die. From more recent work it would appear that an excessive explosive charge must have been used in this forming exercise to have achieved the impact velocity required for welding. Allen, Mapes, and Wilson[2] carried out experiments concerned with the impact of right cylindrical bullets fired at thin targets and they noted a rippling of the surface of the bullet. Abrahamson,[3] who was concerned with the rippling or wave action, continued the work of Allen *et al.* and observed, when firing a steel bullet against an oblique copper target, that adhesion occurred between the steel and the copper; he shows a photomicrograph of the wavy interface typical of explosive welding. This, of course, leads to the conclusion that explosive welding is associated with the oblique impact between the two surfaces to be welded. Crossland and Bahrani[4] also noted that it was well known during the First World War that a bullet or shrapnel could stick to metal surfaces which they impacted, though it was not appreciated that this could be the basis of a welding process.

It is necessary to briefly define welding to get a correct perspective of explosive welding in relation to other welding processes. Simply, welding is a process for joining two or more solid components by local coalescence or union across an interface. The essential conditions for any form of welding are that the two surfaces before welding should be absolutely clean and uncontaminated and that these surfaces should be brought into contact. It is impossible to produce such surfaces by normal mechanical or chemical cleaning processes but under extremely high vacuum conditions Bowden and Tabor[5] and Keller[6] have produced nearly perfectly clean surfaces. If such surfaces are brought into contact, adhesion will occur between the asperities. This adhesion is greatly improved if, in addition to the normal force, a tangential force is applied that is not sufficient to cause sliding.

If two perfectly clean and atomically flat surfaces of the same metal are brought together, interatomic repulsive and attractive forces will come into play and equilibrium will be reached at a particular interatomic distance when the potential energy of the system is a minimum. The strength of the bond will be influenced by factors such as crystallographic misorientation across the interface, and diffusion and recrystallisation, which are very much dependent on temperature. The situation in relation to adhesion of dissimilar metals, which may have not only different atomic spacing but also a different structure, is obviously much more complex but nevertheless adhesion can still occur as a consequence of the interatomic forces.

Various clearly recognisable and distinguishable welding processes have been developed, but all of them are basically processes for removing the contaminant surface layers to allow adhesion to occur between clean metal surfaces. Four distinct welding processes can be recognised. First, there is fusion welding, in which the surfaces of the two metals are melted by the application of heat and the contaminant surface films are brought to the surface of the melt pool or go into solution. Many sources of the heat required for fusion welding have been developed and also methods of reducing the oxidation in the region of the weld. Secondly, there is flow welding, in which a third low-melting-point metal is used together with a suitable flux to wet the surfaces of the solid base metals of the two components to be joined, as for example in brazing, silver soldering, &c. Thirdly, pressure welding, either hot or cold, has been widely practised. In this process the two surfaces to be joined are compressed or hammered together with such force as to cause plastic flow at the interface, with an associated increase in the area of contact. This surface distortion breaks up the contaminant surface film and creates virgin surfaces where adhesion can take place. The effectiveness of the process is greatly improved if surface sliding also occurs during the plastic flow. Finally, we have explosive welding, in which the surface of one of the members is effectively peeled off to form a high-velocity metal jet which scours the surface of the other component. The two clean metal surfaces produced are then pressed together by the explosive pressure.

There are obvious limitations with some of these welding processes. For example, lead with a boiling point of 1620° C (1893 K) could hardly be fusion welded to steel, with a melting point of 1500° C (1773 K). Indeed, it is impossible to weld metals with vastly different melting points by fusion welding. There are, of course, formidable metallurgical problems in fusion welding of some metals and these problems are even more complex when welding together dissimilar metals. Correspondingly, it is unlikely that lead could be pressure welded to steel, as the lead would plastically deform much more readily than the steel and consequently no virgin surface could be produced on the latter. It is apparent that materials of basically different plastic properties cannot be pressure welded together. With explosive welding, melting is not a necessary condition, nor do the plastic properties of the two metals being welded impose any limitations on the process. It is, for example, possible to explosively weld a soft, low-melting-point metal such as lead to a hard, high-melting-point metal.

The main limitation with explosive welding is that, so far, it has proved possible to weld together only very simple

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* Recently our attention has been drawn to an earlier report of welding having occurred under impacting conditions generated by explosives (L. R. Carl, *Metal Progress*, 1944, **46**, (7), 102).

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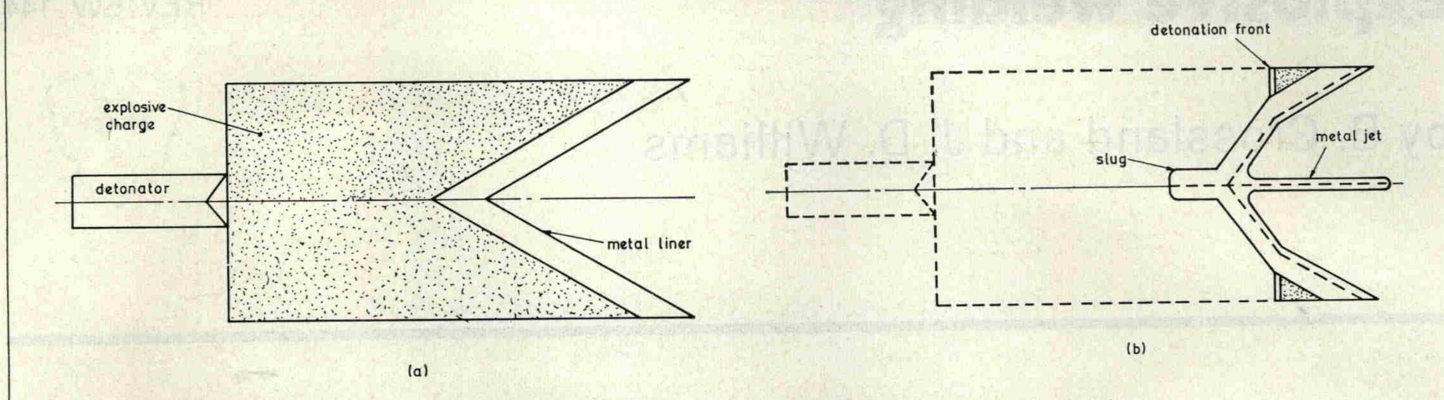


1 Hollow charge with metal liner. (a) Before explosion; (b) collapse of liner and the formation of a metal jet.

geometrical shapes such as flat surfaces, as in cladding, or cylindrical surfaces, as in welding tubes into a tube plate. Other applications have been, or are being investigated, e.g. lap welding, welding of tee junctions, spot welding, production of wire-reinforced composites, &c.

I. Mechanism of explosive welding

Many suggestions have been made regarding the mechanism of explosive welding. Philipchuk[1,7,8] and Zernow *et al.*[9] considered that it was essentially a fusion weld; Davenport,[10] Davenport and Duvall,[11] and Schmidtmann *et al.*[12] regarded it as a cold pressure-welding process; Boes[13] suggested that it was a form of friction welding, while Otto[14] concluded that it involved a shearing action. However, most of the workers in the field, such as Zabelka,[15] Pearson,[16] Hayes and Pearson,[17] Holtzman and Rudeshausen,[18] Cowan and Holtzman,[19] Wright and Bayce,[20] Holtzman and Cowan,[21] Bergmann, Cowan, and Holtzman,[22] Carlson,[23] Bahrani and Crossland,[24] and Bahrani, Black, and Crossland,[25] to mention but a few, have attributed the mechanism of explosive welding to the jetting action that occurs under oblique high-velocity impact.

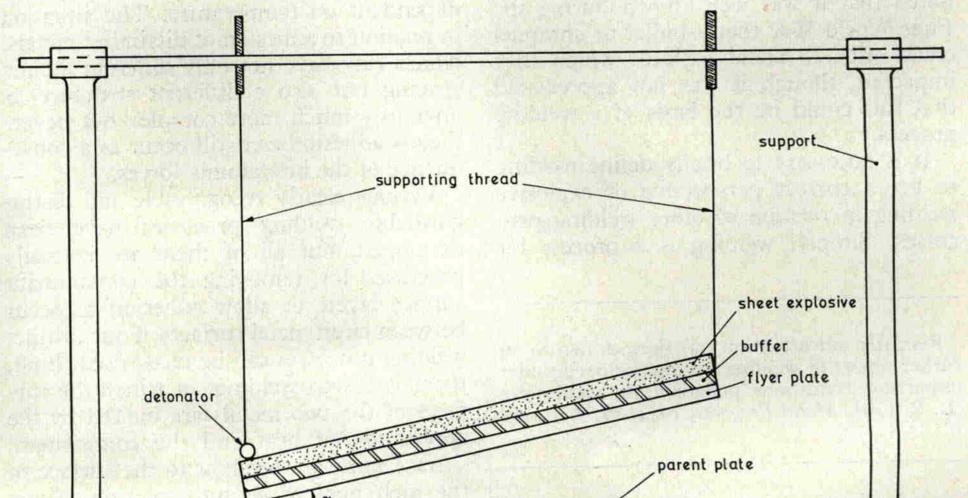
The formation of a metallic jet at the junction between two impacting plates is similar to the jet produced by the collapse of the conical or wedge-shaped liner in a hollow charge, as depicted in Fig. 1, which has been used as a weapon for defeating armour plate. The collapse mechanism and the theory of jet formation in such a case has been given by Birkhoff, MacDougall, Pugh, and Taylor.[26] When the charge is detonated the detonation wave moves down the explosive charge and when it reaches the apex of the liner it subjects the outer surface of the cone to very high pressure which causes its walls to collapse. The pressure produced in the metal in the region where the walls of the liner collide is extremely high, probably of the order of several hundred kilobars, which is much higher than the shear strength of the metal. Consequently, the material in the region of impact behaves as an inviscid fluid and the laws of fluid mechanics can be applied to the situation. It can be shown that the liner material divides into a high velocity 'metallic jet' and a slower-moving slug, as shown in Fig. 1. The high-velocity jet has remarkable powers of penetration. Though this jet behaves in a fluid-like manner it is probable that its temperature is below the melting point, but if it is trapped then the kinetic energy is converted to thermal energy and some melting will occur.

One of the arrangements for welding very commonly adopted is illustrated in Fig. 2. The top or flyer plate is supported with the minimum of constraint at a small angle of incidence, α, relative to the stationary or 'parent plate', which is supported on a relatively massive anvil plate. The top surface of the flyer plate is covered with a protective buffer such as rubber or polystyrene and above that is laid the sheet or layer of high explosive, which is detonated from the lower edge. The detonation of the explosive imparts a velocity V_P to the flyer plate, the magnitude of which depends on the ratio of mass of explosive/unit area to the mass of the flyer plate/unit area. As shown in Fig. 3, the flyer plate collides with the parent plate at an increased angle of incidence, β, and it will be seen that

$$V_P = V_D \sin \varphi = V_D \sin (\beta - \alpha) \quad \ldots [1]$$

As the flyer plate collides with the parent plate it suffers a rapid retardation and an extremely high pressure is generated in both the flyer and parent plates in the region of impact S. As the pressure is very high compared with the shear strength of the materials involved, they behave for a very short interval of time in a similar manner to inviscid fluids and their behaviour can be treated by the laws of hydrodynamics.

It is convenient to bring the point S in



2 Set-up for explosive cladding.